South Afr J Anaesth Analg. 2023;29(5 Suppl 1):S122-124
https://doi.org/10.36303/SAJAA.3042

South Afr J Anaesth Analg
ISSN 2220-1181 EISSN 2220-1173

FCA REFRESHER COURSE

Work, energy, and power

T Jeggo

Department of Anaesthesia, School of Clinical Medicine, Faculty of Health Sciences, Helen Joseph Hospital, University of the Witwatersrand, South Africa
Corresponding author, email: *tahlia.jeggo@gmail.com*

Keywords: work, energy, power, mechanics, physics

Introduction

Mechanics is a section of physics that describes energy and forces and their effect on the motion of bodies.[1] Work, energy, and power are three principles described in mechanics. These three principles are applicable in physiology, as seen in respiration and cardiac output.

Definitions

Work: Work is done when a force applied to an object causes displacement in the same direction as the force.[2] Work (J) = force (N) × distance (m).

Energy: The capacity to do work; measured in joules (J).[3]

Power: The rate at which work is done; measured in watts (W).[4] Power = work (J) / time (seconds).

Work

Work is done when a force applied to an object causes displacement in the same direction as the force.[2] If an object is not displaced despite a force being applied to it, no work is done. The three main components of work include force, displacement, and cause.[3] The SI unit for work is the joule (J), defined as "one joule of work is done when a force of one newton moves its point of application one metre in the direction of the force".[4] One joule is therefore equal to one newton metre. The equation for work is force multiplied by distance (Figure 1).[4]

The equation for work can be modified to be the product of pressure and volume. This is applicable in respiratory physiology to calculate the work of breathing and in cardiac physiology to calculate the work done by the heart.[6] This is done in the following way:

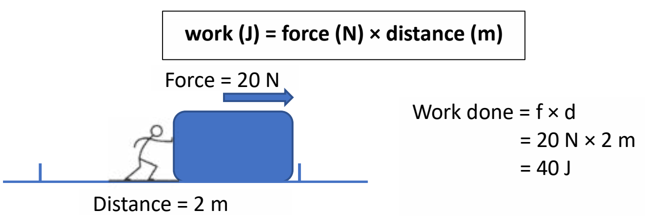

Figure 1: Work done when a force causes a displacement[3]

- pressure = force / area

Therefore:

- force = pressure × area

But:

- work = force × displacement

Therefore:

- work = pressure × area × displacement

However:

- volume = area × displacement

Therefore:

- work = pressure × volume (work = $\Delta P \times \Delta V$)

Energy

Energy is defined as the capacity to do work, measured in joules (J). Energy is essential for work to be performed and is equivalent to work.[3] The conservation of energy principle states that energy cannot be created or destroyed, only transformed from one state to another. Energy exists in many forms and is interchangeable. Mechanical energy exists as either kinetic or potential energy (Figure 2). An object in motion has kinetic energy, which is measured in joules. The energy stored by an object due to its position is potential energy.[3]

mechanical energy = kinetic energy + potential energy

kinetic energy (E_K) = ½ m × v^2

m = mass (kg)

v = velocity ($m.s^{-1}$)

gravitational potential energy (Ep) = m × g × h

m = mass (kg)

g = gravity (9.8 ms^{-2} or 9.8 $N.kg^{-1}$)

h = height (metre)

Figure 2: Calculations for energy

power = work (J) / time (seconds)

However:

- work = force × displacement and velocity = displacement / time
- power = force × distance / time

Therefore:

- power = force × velocity

Figure 3: Calculations for power

Power

Power is defined as the rate at which work is done. It is measured in watts (W).[4] One watt is one joule per second.[6] Power describes the time taken for a force to cause displacement.[3] The equation for power is work divided by time. Since velocity is described as displacement over time, it is possible to describe power as force multiplied by velocity (Figure 3).

Clinical application of work, energy, and power

Respiration

Work of breathing

For the lung and chest wall to move, work needs to be done. During respiration, work is required to overcome elastic forces or elastic recoil from the lungs and chest wall, as well as the airway and tissue resistance. Resistive forces include the airway, tissue, and viscous resistance to airflow.[3,7] In a spontaneously breathing patient, work is performed during inspiration by the respiratory muscles, and by the ventilator in a ventilated patient.

Work done on the lung can be measured using airway pressure and volume change. This is easier to measure in a ventilated patient than in a spontaneously breathing patient.[7] The pressure-volume curve (Figure 4) is used to demonstrate the work of the lung. The striped area indicates work done to overcome the elastic forces, and the dotted area indicates viscous and tissue resistance. The total work done on the lung is the combined striped and dotted areas. An increase in tidal volume will result in an increased elastic work area, whereas an increase in respiratory rate or flow rate will increase the viscous work area.[8]

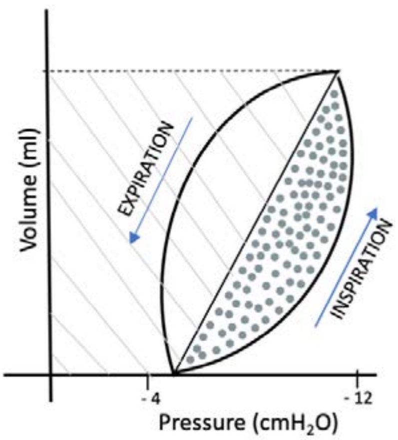

Figure 4: A pressure-volume curve showing work done on the lung during respiration[8]

The total work of breathing is more difficult to measure. It can either be measured by calculating the oxygen cost of breathing (the difference between the total body oxygen uptake [VO_2] in controlled ventilation and the VO_2 with spontaneous ventilation), or by measuring the mechanical work of breathing. Oesophageal pressure (P_{ES}) is used as a reflection of intrapleural pressure, and airway pressure (P_{AW}) is measured. Transpulmonary pressure is then calculated as the difference between the two pressures. P_{AW} represents the work done on the lungs, chest wall, and respiratory apparatus, while transpulmonary pressure is the work done on the lungs only, and transthoracic pressure represents work done on the chest wall (atmospheric pressure minus intrapleural pressure).[7] In a spontaneously breathing patient it is difficult to measure the work of the chest wall.

Expiration is a passive process, but it still requires energy to overcome airway and tissue resistance. Potential energy created by the distention of elastic elements is stored in the chest wall during inspiration and used during expiration.[7,8]

The work of breathing is increased in obstructive lung disease due to an increase in airway resistance. It is also increased in mechanical ventilation due to the use of equipment, such as endotracheal tubes, valves in the circuit, and tubing.[5] Calculating the work of breathing in critically ill patients can assist with weaning ventilator support and guide the timing of extubation.[7]

Energy

During inspiration, mechanical energy is used to overcome elastic and resistive forces. The work done to overcome elastic forces of the lungs and chest wall is stored as potential energy. This potential energy is used for the work of expiration.[3,6,8] The work done to overcome resistive forces is converted to heat energy. An increase in airway resistance or respiratory rate can result in energy requirements that exceed the stored potential energy. Expiration then becomes an active process and expiratory muscles are used.[3]

Power

The type of flow affects the power of breathing. Turbulent flow results in a larger pressure gradient than laminar flow. In laminar flow, pressure is proportional to flow, whereas in turbulent flow, pressure is proportional to the square of flow. When a patient is hyperventilated, the flow becomes turbulent and therefore power increases.[6]

Cardiac

Work of myocardial contraction

As for respiration, the change in volume and pressure can be used to calculate work for each ventricle. Cardiac pressure-volume curves can be used to determine the work of myocardial contractions. Pressure in the left ventricle can be measured using an intraventricular cardiac catheter, and volume can be assessed using echocardiography. Mean arterial pressure and cardiac output are directly proportional to the work of the heart. Therefore, increased cardiac output and hypertension result in increased work of the heart and energy demand.[6]

Power of the heart

The power of the myocardium can be calculated by dividing work by the heart rate. The power of the heart can also be calculated as the product of fluid flow (cardiac output) and pressure difference. The power of the left side of the heart can be calculated using the mean arterial pressure minus the pulmonary venous pressure (in Pa) multiplied by the cardiac output (in m^3s^{-1}). To calculate the power of the right side of the heart, the mean pulmonary artery pressure minus the central venous pressure (in Pa) is multiplied by the cardiac output (in m^3s^{-1}).[6]

ORCID

T Jeggo https://orcid.org/0009-0009-2207-1903

References

1. Merriam-Webster Dictionary. Mechanics definition. Available from: https://www.merriam-webster.com/dictionary/mechanics.
2. Kalsi A, Balani N. Physics for the anaesthetic viva. Cambridge: Cambridge University Press; 2016. p. 9-10. https://doi.org/10.1017/CBO9781316181515.
3. Wilson M. Mechanics: force, mass, acceleration energy, work, power. Anaesth Intensive Care Med. 2020;21(5):256-60. https://doi.org/10.1016/j.mpaic.2020.02.007.
4. Cross ME, Plunkett EVE. Physics, pharmacology and physiology for anaesthetists: key concepts for the FRCA. Cambridge: Cambridge University Press; 2008. p. 21-2. https://doi.org/10.1017/CBO9780511544538.
5. Hill DW. Physics applied to anaesthesia II: mechanics. Brit J Anaesth. 1965;37:710-3. https://doi.org/10.1093/bja/37.9.710.
6. Davis PD, Kenny GNC. Basic physics and measurement in anaesthesia. 5th ed. London: Butterworth-Heinemann; 2003. p. 87-95.
7. French CJ. Work of breathing measurement in the critically ill patient. Anaesth Intensive Care. 1999;27(6):561-73. https://doi.org/10.1177/0310057X9902700602.
8. West JB, Luks AM. West's respiratory physiology: the essentials. 10th ed. Philadelphia: Wolters Kluwer; 2016. p. 134-5.